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SPACECRAFT DYNAMICS CHARACTERIZATION AND CONTROL SYSTEM FAILURE DETECTION

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Semi-Annual Status Report
for the period
February 9, 1990 to August 8, 1990

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SPACECRAFT DYNAMICS CHARACTERIZATION AND CONTROL SYSTEM FAILURE DETECTION

Introduction

This is the report of the status of work under NASA Research Grant No. NAG-1-968 for the period February 9, 1990 to August 8, 1990. The base of technology needed for confident control of large space structures has not yet been developed. No design approach has emerged as being clearly superior to the others nor has an obviously best system architecture been identified. Good ideas and theoretical developments are still needed in every aspect of the design of these control systems - such as design methodology, configuration selection, approaches to fault tolerance, system identification, etc. Additionally, it is becoming increasingly clear that more work needs to be done on stable and reliable numerical algorithms for both the system design function and for operational requirements.

NASA seems well aware of these needs. It is continuing to sponsor an annual conference on Control/Structure Interaction. Moreover, the Control/Structure Interaction (CSI) Program is encouraging research into the problem areas cited above. This program emphasizes the essential step of ground-based demonstration of CSI technology. Such demonstrations bridge the gap between theoretical development and flight test. No flight test activity is included in Phase I of the CSI Program, but that is expected to be forthcoming in later phases. Hopefully this program will be able to stimulate progress in large space structure control technology for a number of years to come and help to establish the base of technology which will enable the missions which both NASA and the Air Force foresee.

Research Progress

The work under this Guest Investigator grant is being directed toward two important aspects of the control of large space structures:

- The modeling of deployed or erected structures including nonlinear joint characteristics

- The detection and isolation of failures of the components of control systems for large space structures

The emphasis in the first task is on efficient representation of the dynamics of large and complex structures having a great many joints. The initial emphasis in the second task is on experimental evaluation of FDI methodologies using ground-based facilities in place at NASA Langley Research Center and Marshall Space Flight Center. Brief summaries follow of the progress to date on both of these research tasks.

Modeling of Structures with Nonlinear Joints

The past six month period has been spent in refining the methodology of modeling trusses with nonlinear joints using describing functions combined with equivalent beam theory. These activities included investigating the calculation of the nonlinear equivalent beam finite element stiffness matrix, investigating the accuracy of the equivalent beam finite element modeling method, using the dual-input describing function to model trusses with nonlinear joints with gravity-induced pre-load undergoing sinusoidal excitation, and building the linear and nonlinear Mini-Mast equivalent beam models.

The previous calculation of the equivalent finite element beam stiffness matrix assumed that the beam displacements were related to the truss displacements by the following equation:

$$\bar{v} = B_e \bar{q}$$

And the strain energy of the truss,

$$U_d = \tfrac{1}{2} q^T [k] q$$

was equated to the strain energy of an equivalent beam:

$$U_e = \frac{1}{2} \bar{v}^T K_e \bar{v}$$

and the difference is minimized. The matrix Be is a rectangular matrix with more columns than rows. The number of truss DOF is more than the number of beam DOF. The equivalent beam stiffness matrix is calculated using the pseudo-inverse:

$$[K_e] = \tfrac{1}{L} \left\{ \left([B_e][B_e]^T \right)^{-1} [B_e][k][B_e]^T \left([B_e][B_e]^T \right)^{-1} \right\}$$

An alternative way of calculating this stiffness matrix is to construct a square Be matrix by including displacements that are not beam-like. For a 2-D beam, this would be some sort of "squeeze" mode. The extra mode of displacement must be orthogonal to the other displacement modes. The Be matrix is now invertible and the equivalent beam stiffness matrix can now be calculated by the following equation:

$$K_e = \tfrac{1}{L} T^T \left[B_e^T \right]^{-1} [k] \left[B_e \right]^{-1} T$$

where T is a transformation matrix that removes the rows and columns with the non-beam-like displacements, thereby constraining these DOF in the finite element methodology.

The investigation of the accuracy of the equivalent finite element beam took the form of building models of a simple cantilevered 2-D truss. There were three types of models, the equivalent beam model with 4 DOF for each section, 6 DOF for each section, and a truss finite element model that has 8 DOF for each section. The number of bays is increased from 1 to 5 and there are two types of trusses, with joints and without joints. The eigenvalues were calculated for each length. Figure 1 is a plot of the percentage difference of the 4 DOF and 6 DOF models from the full 8 DOF truss model, with and without joints. The presence of joints seems to influence the accuracy of the models.

The Dual-Input Describing Function (DIDF) may be adapted to this method of modeling structures to account for the effects of gravity-induced pre-load on a structure with nonlinear joints. The force-displacement-velocity relationship of the joint-truss strut element is of the form:

$$F_{NL}=F(q,\dot{q})$$

If the displacement is assumed to be a harmonic combined with a DC bias:

$$q=B+A\sin\omega t$$

this force relationship can be quasi-linearized to:

$$F=N_B+c_p q+c_q \dot{q}$$

where,

$$N_B=\frac{1}{2\pi B}\int_0^{2\pi} F(B+A\sin\omega t, A\omega\cos\omega t)\, d(\omega t)$$

$$c_p=\frac{1}{\pi A}\int_0^{2\pi} F(B+A\sin\omega t, A\omega\cos\omega t)\sin\omega t\, d(\omega t)$$

$$c_q=\frac{1}{\pi A}\int_0^{2\pi} F(B+A\sin\omega t, A\omega\cos\omega t)\cos\omega t\, d(\omega t)$$

Now when the equations of motion are solved using harmonic balance, there is a third set of equations that are due to the bias terms. These are balanced with the gravity loading on the structure. Figure 2 shows the response of a two bay 2-D truss with piecewise-linear increasing stiffness joints undergoing sinusoidal forcing in the transverse direction,

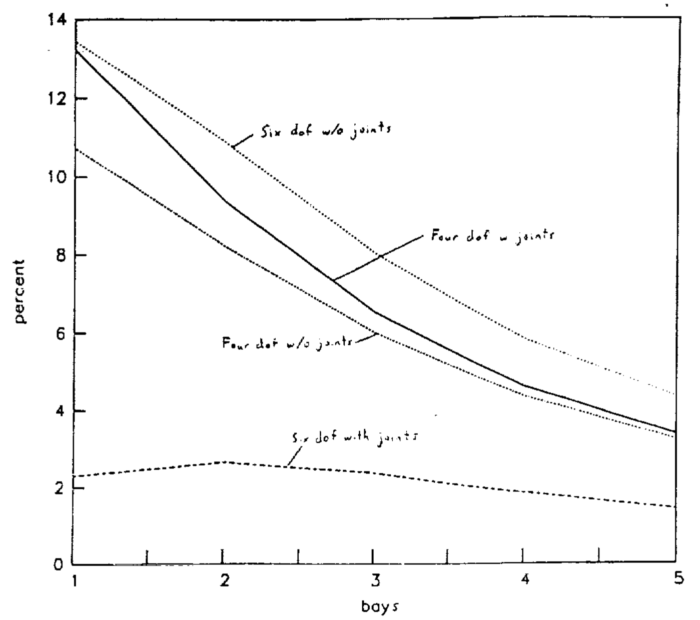


Figure 1. Percent error of reduced beam model first mode frequency compared to full truss model as a function of number of bays in truss.

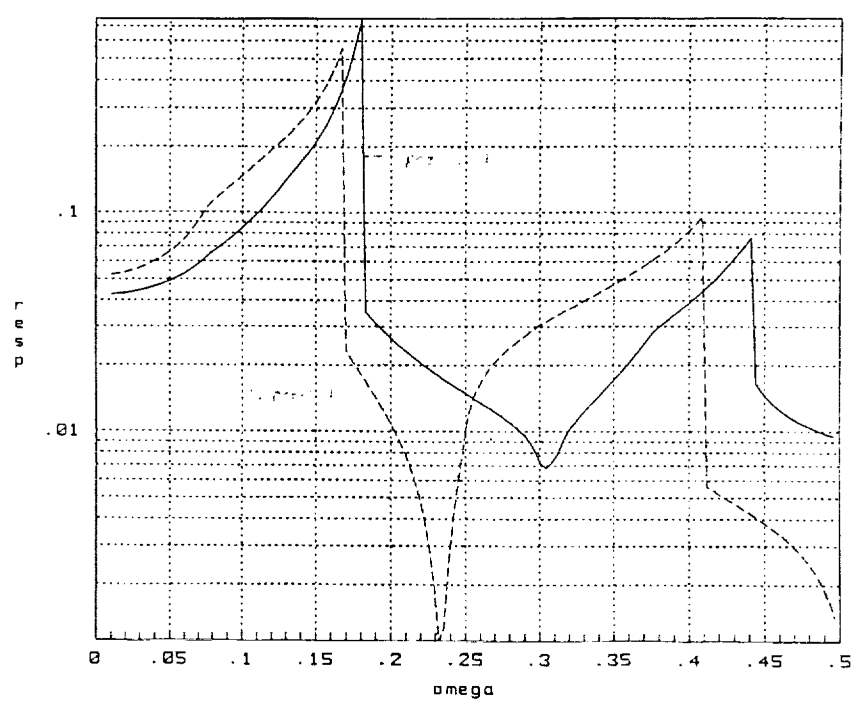


Figure 2. Response of Cantilevered Truss with Piecewise Linear Joints (increasing stiffness with disp) with (Solid line) and without (Dashed line) Gravity Pre-Load.

with and without gravity loading in the longitudinal direction. The gravity loading stiffens the structure and causes changes in the dynamic response.

The type of model used for the Mini-Mast is shown in Figure 3. Also shown is the equivalent beam element corresponding to the truss cell shown. The reduction is from the 9 DOF per truss cell face to 6 DOF per beam element face. The stiffness properties were taken from the Langley finite element model. The truss struts were modeled as rods having only axial stiffness. The following table shows a comparison between four data sets. These are the complete finite element model with 9 DOF per truss face, the reduced equivalent beam model with 6 DOF per element end, the Langley finite element model and experimental modal analysis results of the Mini-Mast itself.

Table 1. Comparison of Models and Experiment for First Five Modes of Mini-Mast

Mode	9 DOF Truss	6 DOF Beam	Langley FE	Exper
1st Bend	0.87 Hz	0.85 Hz	0.81 Hz	0.86 Hz
1st Bend	0.87 Hz	0.86 Hz	0.81 Hz	0.86 Hz
1st Tors	4.034 Hz	4.14 Hz	4.418 Hz	4.19 Hz
2nd Bend	6.91 Hz	6.65 Hz	6.191 Hz	6.11 Hz
2nd Bend	6.91 Hz	6.66 Hz	6.235 Hz	6.18 Hz

The reduced model is especially accurate as compared to the experimental test results.

Finally, the nonlinear model of the Mini-Mast is running. Analytical runs are being made to match stiffness and damping terms with experimental tests and to determine viability of the model. Figure 4 shows results of a sine sweep in the vicinity of the first mode for the Mini-Mast with softening gain changing joints. After further tests, the type of nonlinearity that is believed to be present in the Mini-Mast will be used to match experimental data.

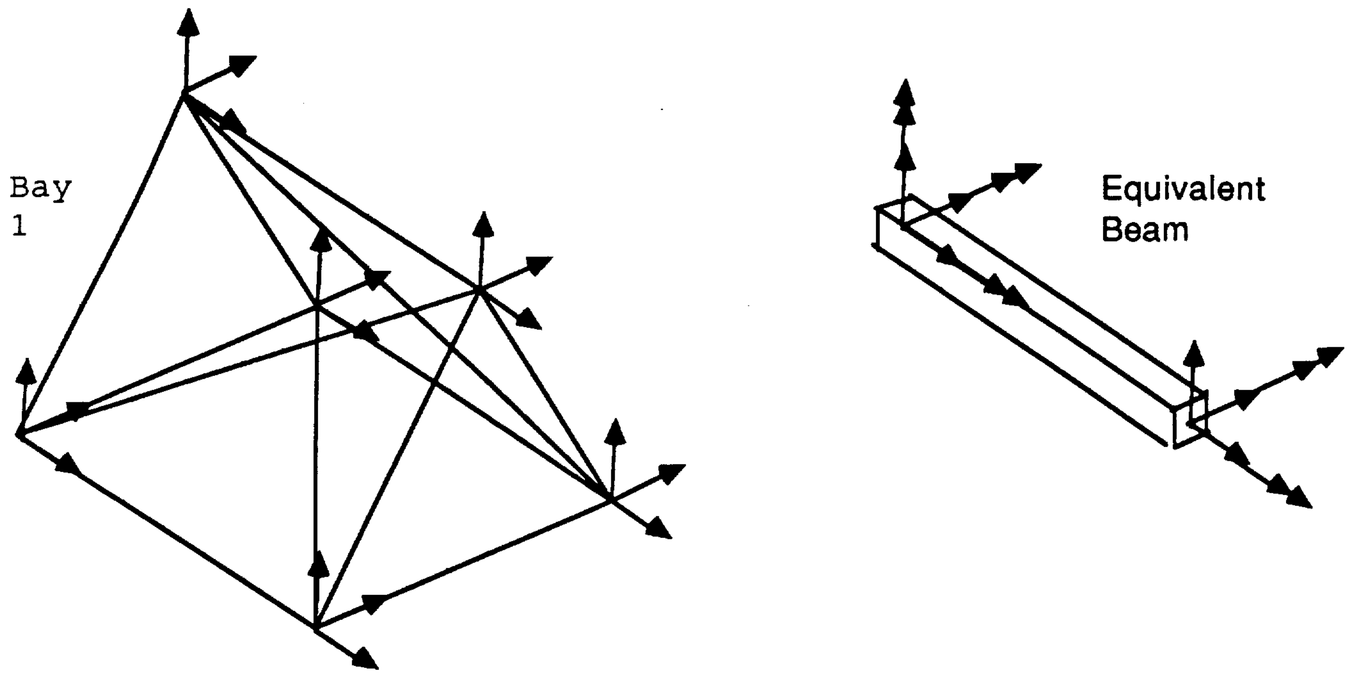


Figure 3. Mini-Mast Model and Equivalent Beam

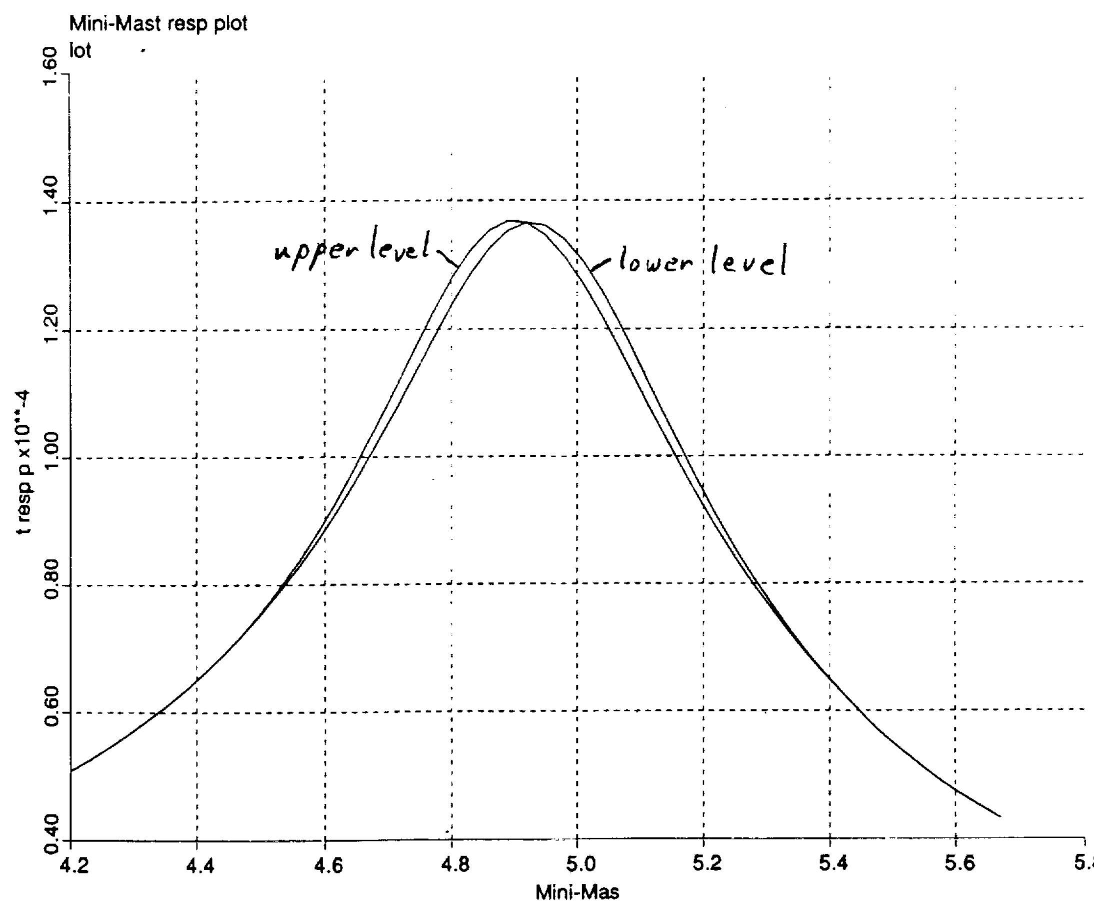


Figure 4. Response of Mini-Mast to two different forcing levels (Transfer function-Y reaction wheel to X-tip translation).

Detection and Isolation of LSS Control System Component Failures

During the period February 1990 - August 1990 we continued analyzing the input-output data recorded during visits to the Mini-Mast facility at NASA Langley Research Center. The method of Generalized Parity Relations was used for all the failure detection tests. The main reason for this choice is that Generalized Parity Relations do not require the specification of failure modes and the corresponding probabilities of failure. The only other method currently available that has similar properties is the failure detection filter. Ultimately, a comparison between these two methodologies will be made.

During the previous phase of the project we completed failure detection experiments of the displacement sensors. During the current period we concentrated on the analysis of the accelerometers and gyros. The X-Y accelerometers and Z-axis gyro at Bay 18 were used and both Single Sensor Parity Relations (SSPR) and Double Sensor Parity Relations (DSPR) were constructed. The X-Y axes gyros were not operational during the time the data was recorded on the Mini-Mast.

A full set of SSPR tests were conducted on the accelerometers and gyro. Because a state-space model is not available for this set of sensors, identified relations were computed from a set of input-output data. Good results were obtained for the accelerometers and gyro for a model order of 20. A typical single sensor parity relation is shown in Figure 5 where the X-axis accelerometer has failed to zero at sample number 250. Figure 6 shows a single sensor parity relation when the Z-axis gyro failed to zero at sample number 240. In both cases we have a clear failure signature. Note further that there is a difference in frequency content of the signal before and after the failure. It was found that filtering the residual improves the failure signature.

The construction of double sensor parity relations is an interesting case when we are dealing with mixed type sensors. A full set of double sensor parity relations were computed for the sensor combinations (Accelerometer X, Accelerometer Y), (Accelerometer X, Gyro Z) and (Accelerometer Y, Gyro Z). Figure 7 shows a typical double sensor parity relation where Accelerometer Y has failed to zero at sample number 230 and in Figure 8 we see the double sensor parity relation residual when the gyro has failed to zero at sample number 220. In both cases we get a clear indication of the failures.

Figure 5. SSPR residual for X-axis Accelerometer

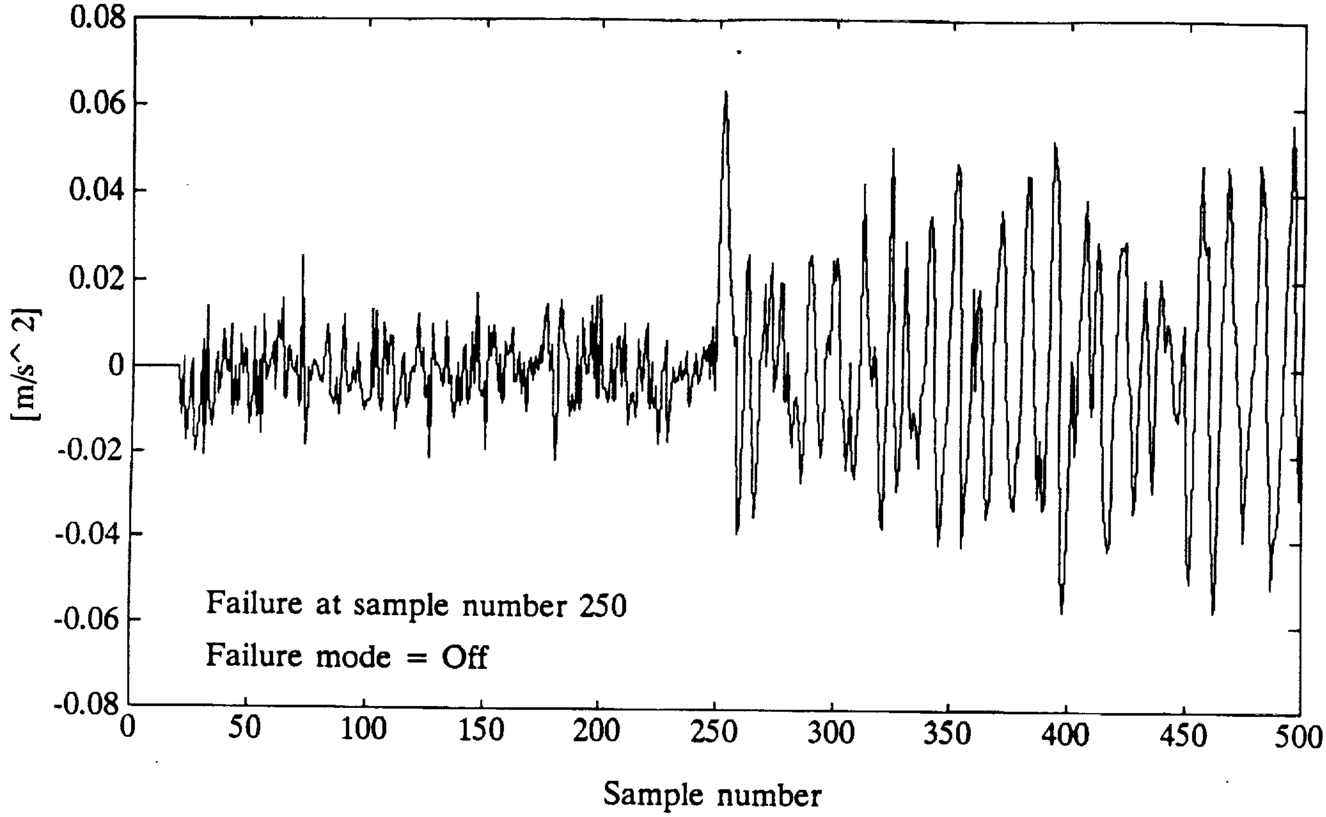


Figure 6. SSPR residual for Z-axis Gyro

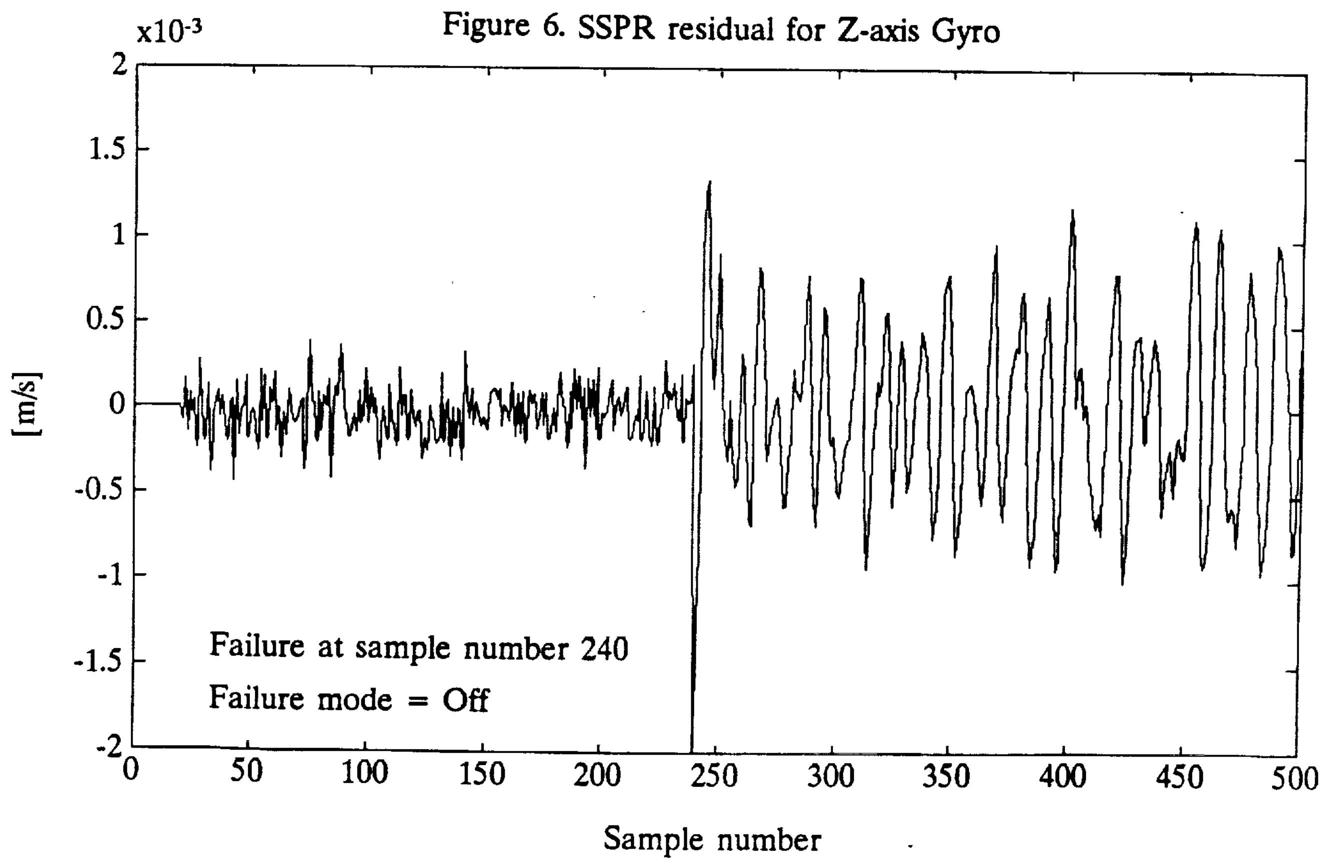


Figure 7. DSPR for (X-axis Acc,Y-axis Acc)

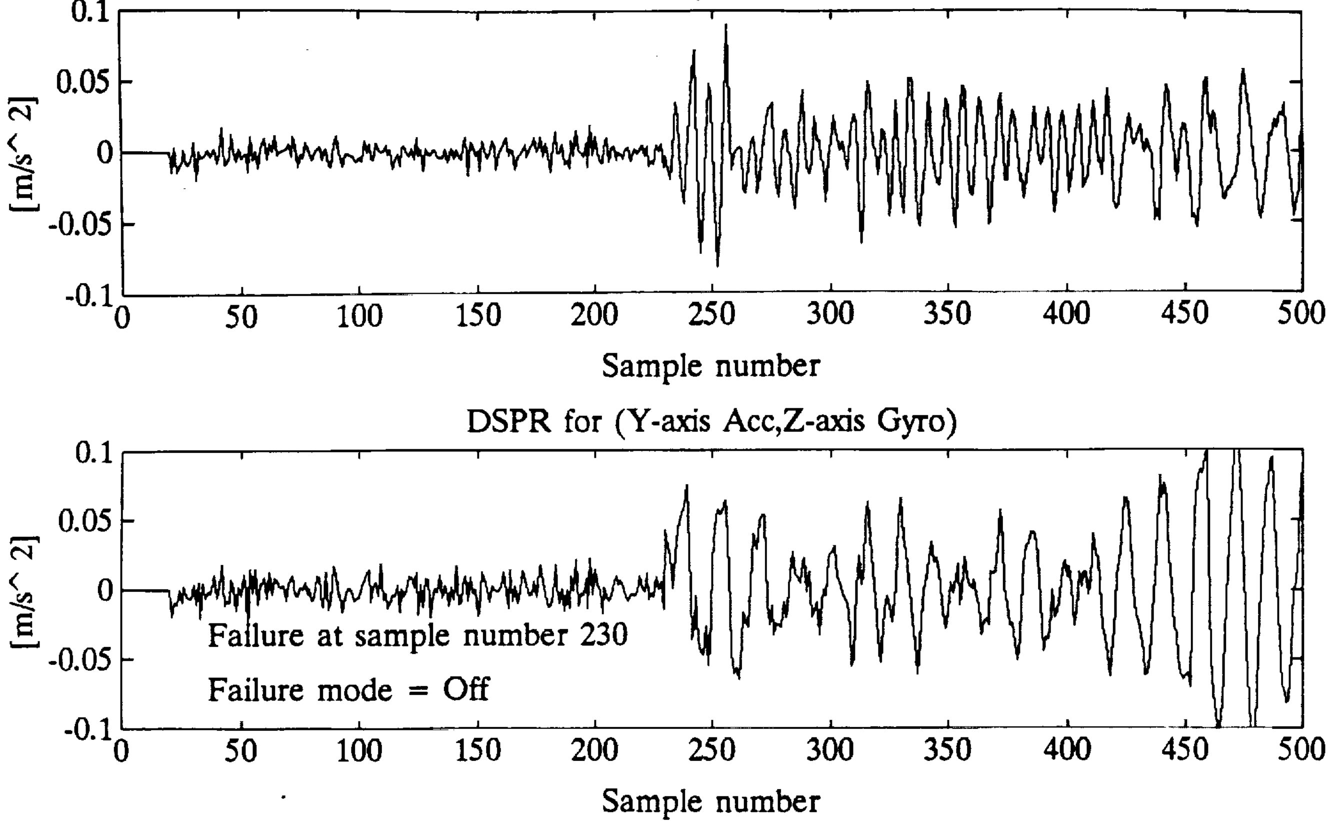
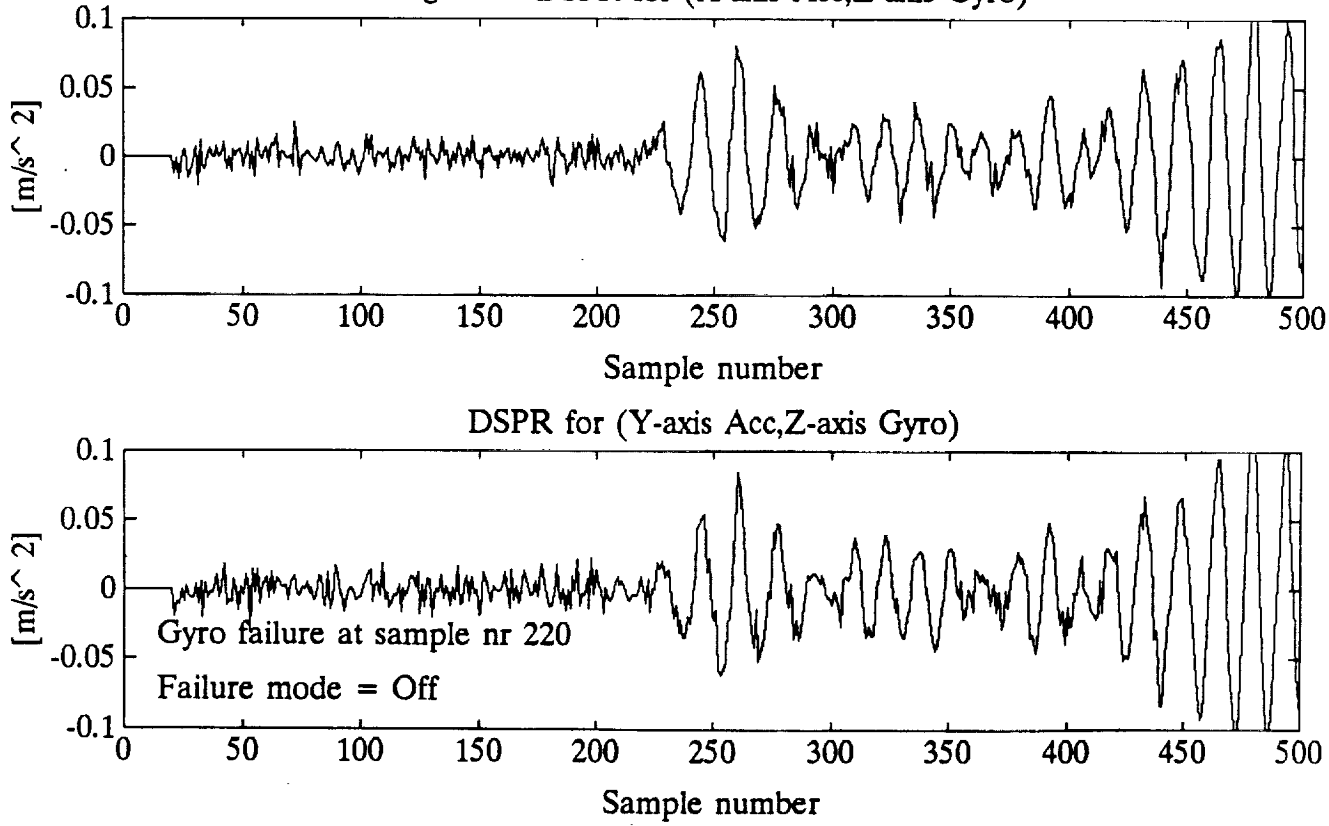


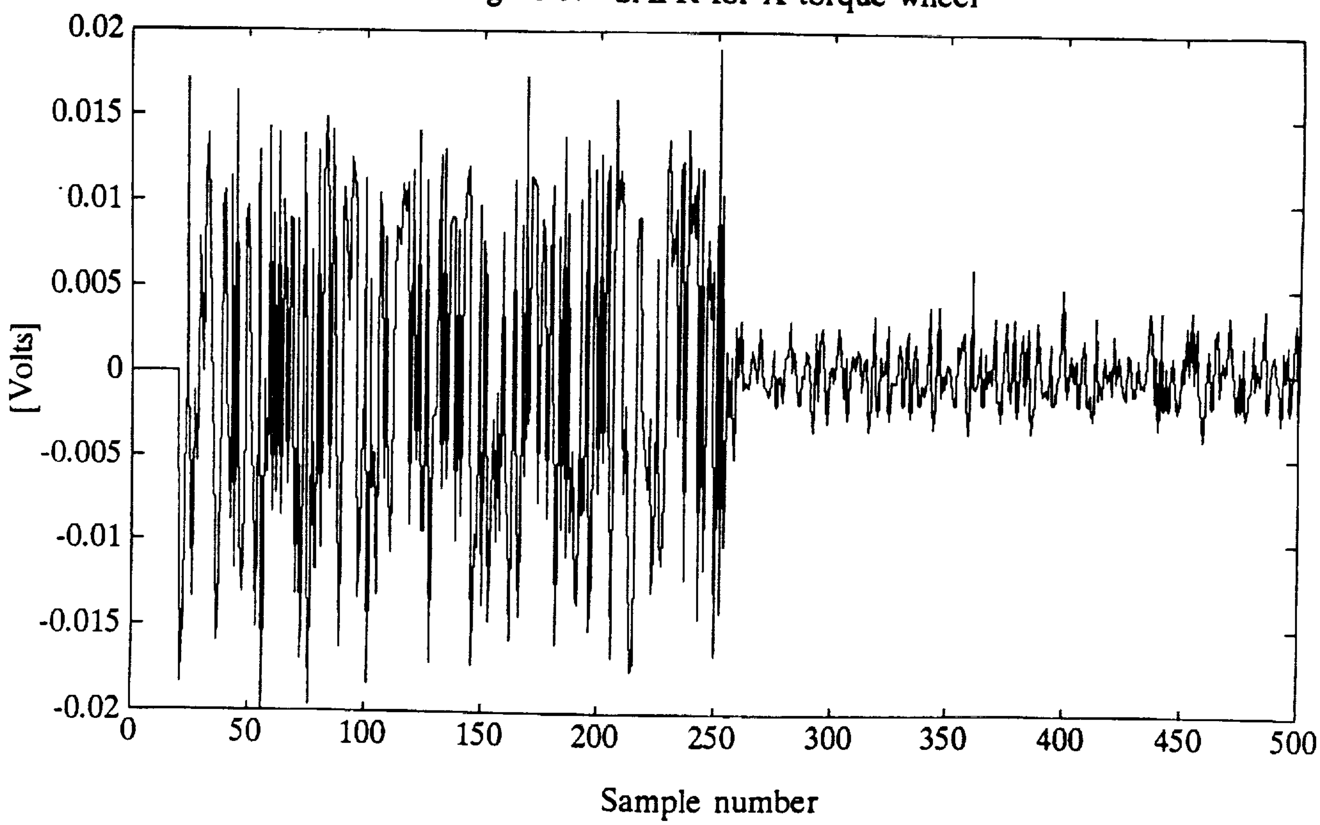
Figure 8. DSPR for (X-axis Acc,Z-axis Gyro)



Experiments were also conducted to analyze the effect of the sampling period on the failure signatures. It was found that increasing the sampling period did not improve the ability of the failure signature to indicate a failure. This is a surprising result as the displacement sensor residuals showed a marked improvement to indicate sensor failures when the sampling period was increased. The reason for this difference is not clear at this point.

Parity relations were also constructed to detect actuator failures. This proved to be very difficult and detecting actuator failures was practically impossible. All possible combinations of single and double actuator parity relations were computed and the effect of increased sampling period was also investigated. One reason for the poor performance of the actuator parity relations was that the residual generators tend to have very high gains at high frequencies, making them very sensitive to noise and high frequency model mismatches. Figure 9 shows a typical single actuator parity relation where the X torque wheel actuator was failed to zero at sample number 250. Although there is a difference in the residual before and after the failure, it is not possible to detect the failure by simply using a threshold detector to indicate that a failure has occurred.

Figure 9. SAPR for X torque wheel



Personnel

The Principal Investigator for this research program is Professor Wallace E. Vander Velde of the MIT Department of Aeronautics and Astronautics. He devotes about 20 percent of his time to this program.

Mark Webster is a graduate student Research Assistant who works full time on this research program. He is a Doctoral candidate in the Department of Aeronautics and Astronautics and he intends to write his Doctoral thesis on the subject of modeling complex space structures with nonlinear joint characteristics.

Christiaan Van Schalkwyk is a graduate student Research Assistant who works full time on this research program. He is a Master's degree candidate in the Department of Aeronautics and Astronautics and he intends to write his Master's thesis on the subject of failure detection and isolation in control systems for large space structures.

Publications and Presentations

Vander Velde, W.E.: "Monitoring the Health of Control System Components," Presentation at the US-Japan Workshop on Smart / Intelligent Materials and Systems, Honolulu, Hawaii, March 19-23, 1990.

Van Schalkwyk, C.M.: "Failure Detection and Isolation on the Mini-Mast Using Generalized Parity Relations," Presentation at the 2nd USAF/NASA Workshop on System Identification and Health Monitoring of Precision Space Structures, California Institute of Technology, Pasadena, California, March 27-29, 1990.

Webster, M.: "The On-Orbit Identification of Nonlinear Systems," Presentation at the 2nd USAF/NASA Workshop on System Identification and Health Monitoring of Precision Space Structures, California Institute of Technology, Pasadena, California, March 27-29, 1990.

Vander Velde, W.E.: "Failure Detection and Isolation Experiments with the Langley Mini-Mast," Presentation at the 1990 American Control Conference, San Diego, California, May 23-25, 1990. The paper also appears in the Proceedings of that conference.

Vander Velde, W.E.: "Spacecraft Dynamics Characterization and Control System Failure Detection," Presentation of the work under this grant at the Mid-Year Review Meeting, Williamsburg, Virginia, July 9 and 10, 1990.